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TITLE

BOREHOLE SURVEYING

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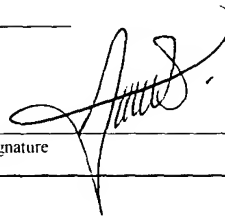
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09/18/03

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1 "Borehole Surveying"

2

3 This invention relates to a method and apparatus for
4 use in surveying of boreholes.

5

6 It is known in directional drilling, for example, to
7 detect the orientation of a drillstring adjacent to
8 the bit by means of a sensor package for determining
9 the local gravitational **[GX,GY,GZ]** and magnetic
10 **[BX,BY,BZ]** field components along mutually
11 orthogonal axes, and to derive from these the local
12 azimuth **(AZ)** and inclination **(INC)** of the
13 drillstring. Conventionally, the measurements are
14 made by providing within the instrument package
15 three mutually perpendicular accelerometers and
16 three mutually perpendicular magnetic fluxgates.

17

18 The present invention is concerned with an
19 arrangement which requires only two measurement
20 devices, namely a single accelerometer and a single
21 magnetic fluxgate or a single accelerometer and a
22 single rate gyro, the latter being preferred for
23 situations in which magnetic interference is likely
24 to be encountered.

25

26 Accordingly, the present invention provides a method
27 of surveying boreholes, comprising:

1 providing an instrument package in the leading
2 end of a drillstring, the instrument package
3 comprising first and second single-axis sensors
4 mounted for rotation with the drillstring about the
5 rotational axis of the drillstring, the first sensor
6 being an accelerometer and the second sensor being a
7 magnetic fluxgate or a rate gyro;

8 rotating the drillstring;

9 deriving from the first sensor the inclination
10 angle of the drillstring at the instrument package;
11 and

12 deriving from the second sensor the azimuth
13 angle of the drillstring at the instrument package.

14
15 Each of the sensors will typically be positioned in
16 one of two configurations. In the first
17 configuration, the sensor is radially spaced from
18 the borehole axis and has its sensing axis in a
19 plane containing the borehole axis and an axis
20 perpendicular thereto. In the second configuration,
21 the sensor is radially spaced from the borehole axis
22 and has its sensing axis in a plane parallel with
23 the borehole axis.

24
25 Preferably, the drilling control rotation angle is
26 also obtained from the sensor outputs.

27
28 Preferably, the sensor outputs are integrated over
29 the four quadrants of rotation and the desired
30 output angle is derived from the integrated output.
31 The instrument package suitably includes rotation
32 angle reference means for use in the integration.

1
2 Additional information may be derived, such as the
3 local gravitational and magnetic field vectors.
4

5 From another aspect, the invention provides
6 apparatus for use in surveying boreholes, the
7 apparatus comprising an instrument package adapted
8 to be included in the leading end of a drillstring,
9 the instrument package comprising first and second
10 single-axis sensors mounted for rotation with the
11 drillstring about the rotational axis of the
12 drillstring, the first sensor being an accelerometer
13 and the second sensor being a magnetic fluxgate or a
14 rate gyro; and computing means for deriving from the
15 first sensor while the drillstring is rotating the
16 inclination angle of the drillstring at the
17 instrument package, and for deriving from the second
18 sensor while the drillstring is rotating the azimuth
19 angle of the drillstring at the instrument package.
20

21 The computing means preferably operates to integrate
22 the sensor outputs over the four quadrants of
23 rotation and to derive the desired output angle
24 from the integrated output.
25

26 The apparatus may further include rotation angle
27 reference means for use in the integration.
28

29 Examples of the present invention will now be
30 described, by way of illustration only, with
31 reference to the drawings, in which:
32

1 Fig. 1 illustrates, in general terms, the
2 operation of a single axis sensor in a drillstring
3 for sensing any given vector V ;

4 Fig. 2 is a block diagram of one circuit which
5 may be used to identify rotation quadrant;

6 Fig. 3 illustrates the operation where the
7 sensor is an accelerometer;

8 Fig. 4 illustrates the operation where the
9 sensor is a fluxgate;

10 Fig. 5 illustrates the derivation of azimuth
11 angle; and

12 Fig. 6 illustrates the operation where the
13 sensor is a rate gyro.

14

15

16 Single-axis sensor

17

18 The operation of a single-axis sensor in a drill
19 string will first be described in general terms.
20 The application of this to specific sensors is
21 discussed below.

22

23 Referring to Fig. 1, a single-axis sensor 10 is
24 mounted on a drill string (not shown). The sensor
25 10 senses a fixed vector $\{V\}$ and is mounted in one
26 of two configurations.

27

28 In the first configuration, the sensor 10 lies in a
29 plane containing the rotation axis (OZ) of the drill
30 string and axis (OX) perpendicular to (OZ) . Axis
31 (OY) makes up the conventional orthogonal set of
32 axes $[OX, OY, OZ]$. The sensor 10 is mounted at a

1 distance r from the (OZ) axis and the angle between
 2 the sensing axis (OS) and the rotational axis (OZ)
 3 is m .

4

5 In the second configuration, the sensor 10 is
 6 mounted in a plane which is parallel to the borehole
 7 axis (OZ) and with its sensing axis perpendicular to
 8 the axis (OY) and making angle m with the direction
 9 of the borehole axis (OZ).

10

11 If the rate of rotation about the (OZ) axis is w and
 12 the components of $\{V\}$ are $\{VOZ\}$ along the (OZ) axis
 13 direction and $\{VOXY\}$ in the (OXY) plane, then if the
 14 output from the sensor 10 for both configuration 1
 15 and configuration 2 of Figure 1 is of the form

16

$$17 \quad V(t) = VOZ.\cos(m) + VOXY.\sin(m).\cos(w.t) + c$$

18

19 where time $t = 0$ when the axis (OX) is coincident
 20 with the direction of $\{VOXY\}$ and c is constant for
 21 any fixed rotation rate w .

22

23 Thus, the sensor output at time t can be written:

24

$$25 \quad V(t) = K1.\cos(w.t) + K2 \quad \dots\dots\dots(i)$$

26

27 where $K1 = VOXY.\sin(m)$ and $K2 = VOZ.\cos(m) + c$ are
 28 constant if the vector amplitudes VOZ and $VOXY$ are
 29 constant.

30

1 Sensor output integration

2

3 The integration of $V(t)$ from any initial time t_i to
 4 $t_i + T/4$, where $T = 2\pi/w$, the time for one
 5 revolution about (OZ), is

6

$$7 \quad Q = \int_{t_i}^{t_i+T/4} K1.\cos(wt).dt + \int_{t_i}^{t_i+T/4} K2.dt$$

8

9 Thus,

$$10 \quad \quad \quad t_i + T/4$$

$$11 \quad Q = [(K1/w).\sin(w.t)] \quad + K2.T/4$$

$$12 \quad \quad \quad t_i$$

13

14 or

15

$$16 \quad Q = (K1/w).[\sin(w.t_i + w.T/4) - \sin(w.t_i)] + L$$

17

18 or

$$19 \quad Q = (K1/w).[\sin(w.t_i + \pi/2) - \sin(w.t_i)] + L$$

20 or

$$21 \quad Q = (K1/w).[\cos(w.t_i) - \sin(w.t_i)] + L \quad \dots\dots(ii)$$

22 where L is a constant $= K2.T/4$.

23

24 Using equation (ii), the integration of $V(t)$ from an
 25 arbitrary time t_0 to time $t_0+T/4$ yields

26

$$27 \quad Q1 = (K1/w).[\cos(w.t_0) - \sin(w.t_0)] + L \quad \dots\dots(iii)$$

28

29 Using equation (ii), the integration of $V(t)$ from
 30 time $t_0+T/4$ to time $t_0+T/2$ yields

31

$$Q_2 = (K_1/w) \cdot [\cos(w.t_0 + w.T/4) - \sin(w.t_0 + w.T/4)] + L$$

or

$$Q_2 = (K_1/w) \cdot [\cos(w.t_0 + \pi/2) - \sin(w.t_0 + \pi/2)] + L$$

or

$$Q_2 = (K_1/w) \cdot [-\sin(w.t_0) - \cos(w.t_0)] + L \quad \dots (iv)$$

6

Using equation (ii), the integration of $V(t)$ from time $t_0 + T/2$ to $t_0 + 3T/4$ yields

9

$$Q_3 = (K_1/w) \cdot [\cos(w.t_0 + w.T/2) - \sin(w.t_0 + w.T/2)] + L$$

or

$$Q_3 = (K_1/w) \cdot [\cos(w.t_0 + \pi) - \sin(w.t_0 + \pi)] + L$$

or

$$Q_3 = (K_1/w) \cdot [-\cos(w.t_0) + \sin(w.t_0)] + L \quad \dots (v)$$

15

Using equation (ii), the integration of $V(t)$ from time $t_0 + 3T/4$ to time $t_0 + T$ yields

18

$$Q_4 = (K_1/w) \cdot [\cos(w.t_0 + w.3T/4) - \sin(w.t_0 + w.3T/4)] + L$$

or

$$Q_4 = (K_1/w) \cdot [\cos(w.t_0 + 3\pi/2) - \sin(w.t_0 + 3\pi/2)] + L$$

or

$$Q_4 = K_1/w \cdot [\sin(w.t_0) + \cos(w.t_0)] + L \quad \dots (vi)$$

24

Writing $K = K_1/w$ and $\alpha = w.t_0$, then equations (iii) through (vi) yield for the four successive integrations of $V(t)$

28

$$Q_1 = -K \cdot \sin \alpha + K \cdot \cos \alpha + L \quad \dots (vii)$$

$$Q_2 = -K \cdot \sin \alpha - K \cdot \cos \alpha + L \quad \dots (viii)$$

$$Q_3 = K \cdot \sin \alpha - K \cdot \cos \alpha + L \quad \dots (ix)$$

$$1 \quad Q4 = K.\sin\alpha + K.\cos\alpha + L \quad \dots\dots\dots(x)$$

2

3 Integration control

4

5 In order to control the sensor output integration,
 6 as just described, over four successive quarter
 7 periods of the drill string rotation, a train of n
 8 (with n any multiple of 4) equally spaced pulses per
 9 revolution must be generated. If one pulse P_0 of
 10 this pulse train is arbitrarily chosen at some time
 11 t_0 , the repeated pulses $P_{n/4}$, $P_{n/2}$ and $P_{3n/4}$ define
 12 times $t_0+T/4$, $t_0+T/2$ and $t_0+3T/4$ respectively where
 13 the period of rotation $T = 2\pi/w$ and w is the angular
 14 velocity of rotation.

15

16 A suitable means for generating an appropriate
 17 control pulse train is described in US-A1-
 18 20020078745, which is hereby incorporated by
 19 reference.

20

21 In an alternative form of integration control, the
 22 sensor output waveform itself can be used with
 23 appropriate circuitry for defining the integration
 24 quadrant periods. In particular, the relatively low
 25 noise magnetic fluxgate output is well suited to act
 26 as input to a phase-locked-loop arrangement. Fig. 2
 27 shows such an arrangement, successive output pulses
 28 defining the integration quadrants.

29

30 Rotation angle

31

Equations (vii) through (x) can be solved to yield angle α ; there is a degree of redundancy in the possible solutions but, for example,

$$Q1 - Q2 = 2K.\cos\alpha$$

and

$$Q3 - Q2 = 2K.\sin\alpha$$

or

$$\sin\alpha/\cos\alpha = (Q3-Q2)/(Q1-Q2) \quad \dots\dots(x_i)$$

10

Since $\alpha = w.t_0$, the angle $S(t_0)$ between the axis (OX) and the direction of {VOXY} at time t_0 can be determined from equation (xi), and the angle between (OX) and {VOXY} at any time t_m measured from the arbitrary starting time t_0 is then

16

$$S(t_m) = \alpha + w.t_m = S(t_0) + 2\pi.t_m/T \quad \dots(x_{ii})$$

18

Magnitudes of vectors {VOXY} and {VOZ}

20

Equations (vii) through (x) can be solved to yield the constant L:

23

$$L = (Q1 + Q2 + Q3 + Q4)/4 \quad \dots\dots(x_{iii})$$

25

and the constant K can be determined from:

27

$$(K)^2 = [(Q1-L)^2 + (Q2-L)^2]/2$$

$$= [(Q3-L)^2 + (Q4-L)^2]/2 \quad \dots(x_{iv})$$

30

The magnitude of vector {VOZ} can be determined as

31

1
 2 $VOZ = (K2 - c) / \cos(m) = (4.L/T - c) / \cos(m) \quad \dots(xv)$
 3 provided that constant c is known.

4
 5 The magnitude of vector $\{VOXY\}$ can be determined as

6
 7 $VOXY = K1 / \sin(m) = (K.w) / \sin(m) \quad \dots\dots(xvi)$

8
 9 Inclination angle

10
 11 The inclination angle (INC) can be derived from the
 12 gravity vector $\{G\}$ with the aid of a rotating
 13 accelerometer.

14
 15 Referring to Fig. 3, where (INC) is the angle
 16 between the tool axis (OZ) and the gravity vector
 17 $\{G\}$,

18
 19 $GOZ = G \cdot \cos(INC) \quad \dots(xvii)$

20 and

21 $GOXY = -G \sin(INC) \quad \dots\dots(xviii)$

22
 23 The accelerometer output can be written as

24
 25 $VG(t) = GOZ \cdot \cos(m) + GOXY \cdot \sin(m) \cdot \cos(wt)$
 26 $\quad + CP \cdot \sin(m) + D \cdot \sin(m) \quad \dots\dots\dots(xix)$

27
 28 where CP is a centripetal acceleration term and D is
 29 a sensor datum term. The centripetal acceleration
 30 term CP is zero for configuration 2 and makes this
 31 the preferred configuration for mounting of the
 32 accelerometer.

1
2 Since **CP** is proportional to w^2/r and is constant for
3 constant **w**, then clearly **VG(t)** is of the form
4
5
$$\mathbf{VG}(t) = K1.\cos(w.t) + K2(w)$$

6 (or $K1.\cos(w.t) + K2$ for configuration 2)(**xx**)
7
8 where **K1** and **K2(w)** are constants at constant angular
9 velocity **w** in the case of configuration 1 and always
10 constant in the case of configuration 2. the
11 constants **K1** and **K2(w)** can be determined from the
12 accelerometer output integrations as described above
13 together with the angle (**Highside Angle HS = w.t**)
14 between the axis (**OX**) and the direction of **{GOXY}**.
15
16
$$K1 = GOXY.\sin(m) \quad \text{.....(xxi)}$$

17 and
18
$$K2(w) = GOZ.\cos(m) + D.\sin(m) \quad \text{.....(xxii)}$$

19 with
20
$$C(w) = CP.\sin(m) + D.\sin(m) \quad \text{.....(xxiii)}$$

21 constant at constant angular velocity **w** (or for
22 configuration 2 at all **w**).
23
24 A calibration procedure can be carried out to
25 determine the values of **C(w)** for angular velocity
26 values **w** (constant in the case of configuration 2)
27 by calculating values of **K2(w)** with the rotation
28 axis (**OZ**) horizontal when **C(w) = K2(w)**.
29
30 Thus, for any drilling situation with known angular
31 velocity **w**, the vector components of the local
32 gravity vector **{G}** can be determined as

7

$$2 \quad \text{GOXY} = K1/\sin(m) \quad \dots\dots\dots(\text{xxiv})$$

3 and

```
4      GOZ = (K2(w) - C(w))/cos(m)          .....(xxv)
```

5

6 The inclination angle (**INC**) can then be determined

7 from

8

9 $\sin(\text{INC})/\cos(\text{INC}) = -\text{GOXY}/\text{GOZ} \quad \dots\dots(\text{xxvi})$

10

11 Azimuth angle

12

13 When using a rotating fluxgate, the azimuth angle

14 **(AZ)** can be determined from a consideration of the

15 magnetic vector $\{\mathbf{B}\}$. What follows is applicable to

16 both configuration 1 and configuration 2.

17

18 With reference to Fig. 4, it can be shown that

19

```
20      BOZ = BV*cos( INC)
```

```
21      + BN.cos(AZ).sin(INC)      ....(xxvii)
```

22

23 and

24

```
25      BOXY = (BN.cos(AZ).cos(INC)-BV.sin(INC)).cos(HS-MS)
```

```
26      + BN.sin(AZ) .sin(HS-MS)      .....(xxviii)
```

27

28 or, with $HS-MS = d$ a constant,

29

```
30  BOXY = (BN.cos(AZ).cos(INC)-BV.sin(INC)).cos(d)
```

```

31      +BN.sin(AZ).sin(d)          .....(xxix)

```

32

1 With **D** the fluxgate datum, the fluxgate output can
 2 be written

$$3$$

$$4 \quad VB(t) = BOZ.\cos(m) + BOXY.\sin(m).\cos(w.t)$$

$$5 \quad \quad \quad + D.\sin(m) \quad \quad \quad \text{.....(xxx)}$$

6 or

$$7 \quad VB(t) = K1.\cos(w.t) + K2 \quad \quad \quad \text{.....(xxxi)}$$

8 where

$$9 \quad K1 = BOXY.\sin(m)$$

10 and

$$11 \quad K2 = BOZ.\cos(m) + D.\sin(m)$$

$$12 \quad \quad = BOZ.\cos(m) + C \quad \quad \quad \text{.....(xxxii)}$$

13

14 are constants which can be determined from the
 15 fluxgate output integrations as described above
 16 together with the angle (**Magnetic Steering Angle =**
 17 **MS = w.t**) between the axis (**OX**) and the direction of
 18 **{BOXY}**.

19

20 A calibration procedure can be carried out to
 21 determine the value of the constant **C** by calculating
 22 the value of **K2** while rotating about the direction
 23 of the axis (**OZ**) along which **BOZ = 0** when **K2 = C**.

24

25 Thus, for any drilling situation the vector
 26 components of the local magnetic field **{B}** can be
 27 determined as

28

$$29 \quad BOXY = K1/\sin(m) \quad \quad \quad \text{.....(xxxiii)}$$

30 and

$$31 \quad BOZ = (K2-C)/\cos(m) \quad \quad \quad \text{.....(xxxiv)}$$

32

1 With reference to Fig. 5, the horizontal component
 2 {BN} of the local magnetic field vector {B} can be
 3 represented by horizontal components {B1} and {B2}
 4 where

5

$$6 \quad B1 = BOXY.\cos(d).\cos(INC) \\
 7 \quad \quad \quad + BOZ.\sin(INC) \quad \dots\dots(xxxv)$$

8 and

$$9 \quad B2 = BOXY.\sin(d) \quad \dots\dots\dots(xxxvi)$$

10

11 The Azimuth Angle (AZ) can then be determined from

12

$$13 \quad \sin(AZ)/\cos(AZ) = -B2/B1 \quad \dots\dots\dots(xxxvii)$$

14

15 Also, the horizontal component of the local magnetic
 16 field can be determined from

17

$$18 \quad BN = (B1^2 + B2^2)^{3/2} \quad \dots\dots\dots(xxxviii)$$

19

20 and the vertical component of the local magnetic
 21 field can be determined from

22

$$23 \quad BV = BOZ.\cos(INC) \\
 24 \quad \quad \quad - BOXY.\cos(d).\sin(INC) \quad \dots\dots(xxxix)$$

25

26 Earth's rotation vector

27

28 Where it is not practicable to use a magnetic
 29 fluxgate, this may be replaced by a rate gyro as
 30 sensor.

31

1 With reference to Fig. 6, if the geographic latitude
 2 at the drilling location is (LAT) then the vertical
 3 component of the earth's Rotation Vector {RE} is

4

$$5 \quad RV = -RE.\sin(LAT) \quad \dots\dots\dots(xl)$$

6 and the horizontal component is

$$7 \quad RN = RE.\cos(LAT) \quad \dots\dots\dots(xli)$$

8

9 The magnitude of the cross-axis rate vector {ROXY}
 10 can be shown to be

11

$$12 \quad ROXY = (RN.\cos(GAZ).\cos(INC) - RV.\sin(INC)).\cos(d) \\ 13 \quad \quad \quad + RN.\sin(GAZ)\sin(d) \quad \dots\dots\dots(xlii)$$

14

15 where (GAZ) is the gyro azimuth angle and

16 $d = HS - GS$ is constant.

17

18 Since RN, RV, d and INC are known and ROXY can be
 19 derived as discussed below, (GAZ) can be determined.

20

21 With the particular configuration where the rate
 22 gyro sensing axis is perpendicular to the drill
 23 string rotation axis (OZ), the rate gyro output can
 24 be written

25

$$26 \quad VG(t) = ROXY.\cos(w.t) + D \quad \dots\dots\dots(xliii)$$

27

28 where D is the rate gyro datum, or

29

$$30 \quad VG(t) = K1.\cos(w.t) + K2 \quad \dots\dots\dots(xliv)$$

31

1 where the constant **K1 = ROXY** can be determined from
2 the rate gyro output integrations as described above
3 together with the Gyro Steering Angle **GS = w.t**
4 between **(OX)** and the direction of **{ROXY}**.

5
6 The variation in the Rate Gyro Datum makes it
7 difficult to achieve satisfactory datum calibration
8 in all circumstances. It is unlikely that Gyro
9 Azimuth measurements should be attempted at high
10 inclination angles. The use of the rate gyro is
11 most likely with near-vertical boreholes in
12 locations where magnetic azimuth measurements are
13 unreliable (such as close to rigs) and the Gyro
14 Azimuth **GAZ** is approximately equal to the angle **d**.

15
16 The present invention thus makes possible the
17 measurement of a number of borehole-related
18 parameters during rotation of a drillstring and
19 using a reduced number of sensors. Modifications
20 may be made to the foregoing embodiments within the
21 scope of the present invention.